

SeaWiFS and MODIS-Aqua C_a Retrievals in Chesapeake Bay

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and the
NASA Ocean Biology Processing Group

Review

SeaWiFS Chesapeake Bay C_a algorithm round-robin conducted in 2006 ~ hosted by CBP, executed by NASA, with input from UMD, ODU, and NOAA

analysis results posted online at http://seabass.gsfc.nasa.gov/eval/cbp_eval.cgi

SeaWiFS C_a images generated daily by NOAA Coastwatch - East Coast Node and posted online at http://coastwatch.chesapeakebay.noaa.gov/cb_seawifs.html

ALGORITHMS

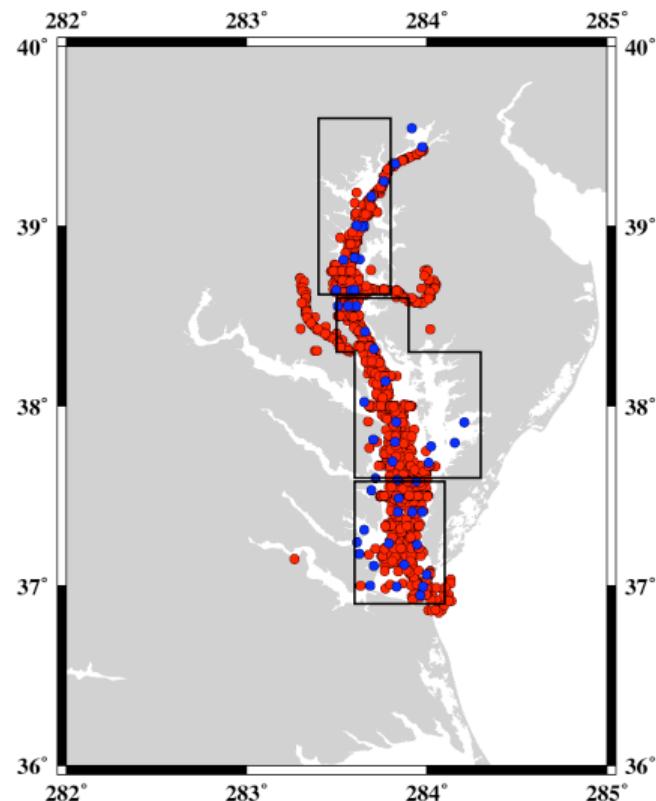
empirical (statistical) approaches

| | |
|--------|---------------------|
| OC4 | operational SeaWiFS |
| OC3 | operational MODIS |
| OC2 | |
| OC3-CB | tuned to Bay (ODU) |
| Clark | tuned to Bay (NOAA) |
| Carder | operational VIIRS |

semi-analytical approaches

| | |
|----------|--------------------|
| GSM01 | |
| GSM01-CB | tuned to Bay (UMD) |

GROUND TRUTH

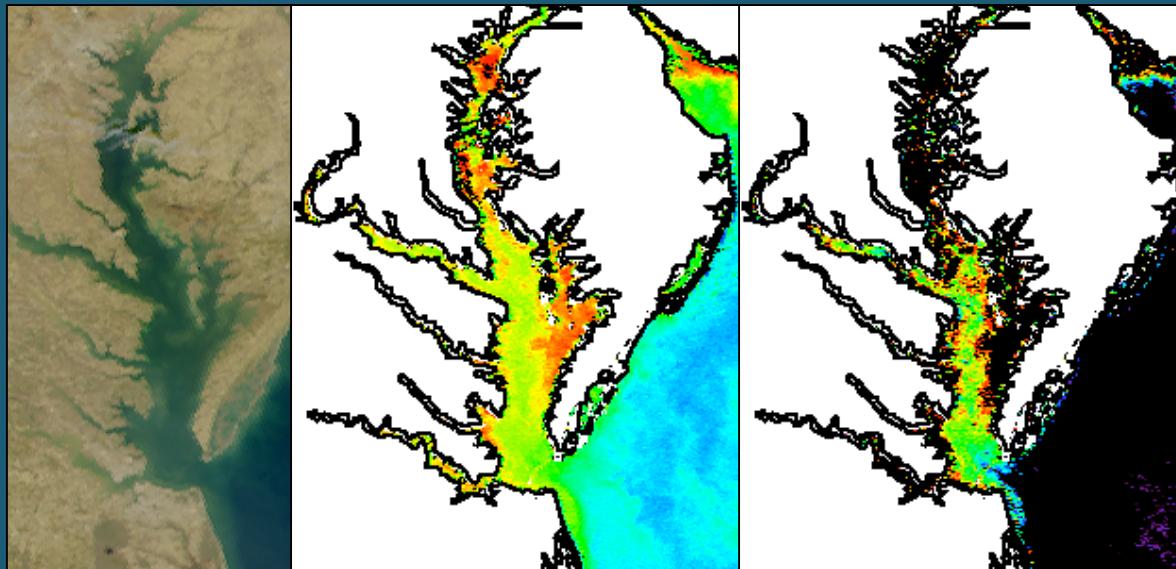


SIMBIOS/Harding (3,000 stations)

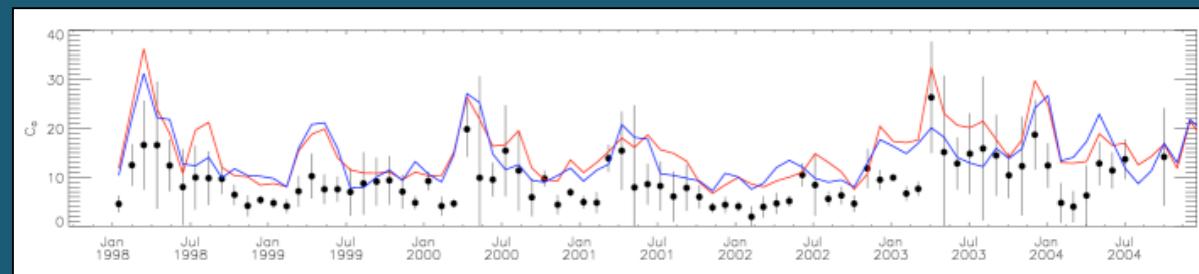
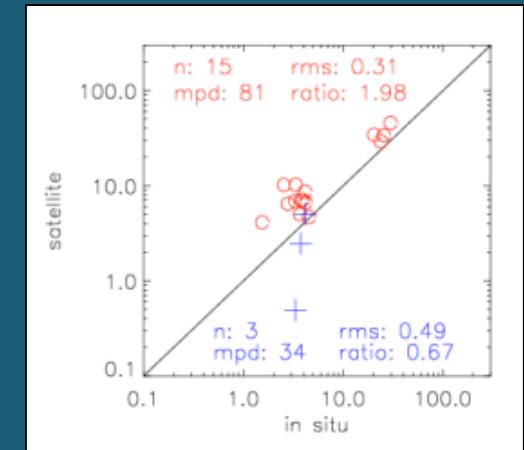
CBP (15,000 stations)

stratification following Magnuson et al. 2004

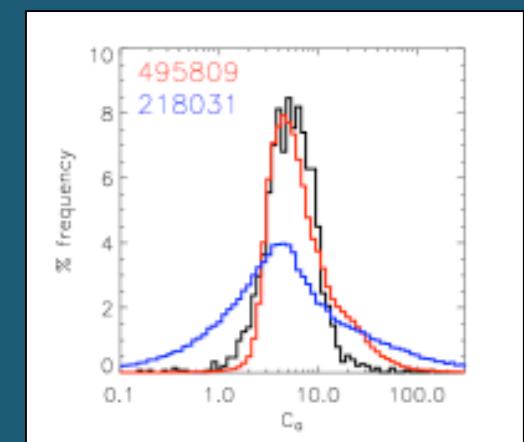
COVERAGE



L2 MATCH-UPS



TIME-SERIES



DISTRIBUTIONS

the histograms, time-series, scatter plots, and maps convey comparative information in rather different ways

trade-offs in specific coverage needs and accuracy requirements drive the selection of the best algorithm(s) and processing approach(es)

currently running MODIS-Aqua time-series (Jun 2002 to present)

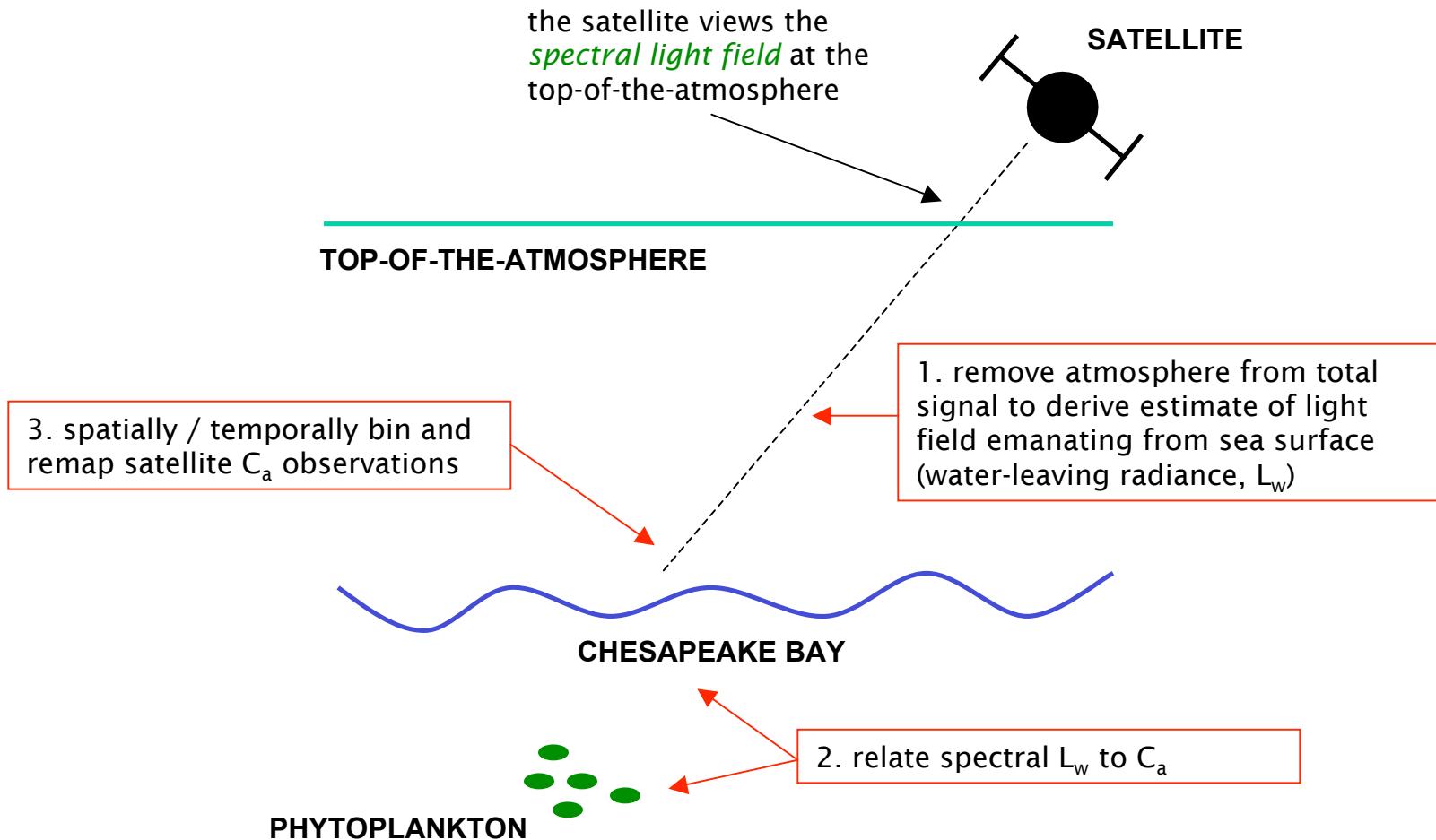
will rerun SeaWiFS data with current version of MSL12 and C_a algorithms

received aircraft data from Larry Harding

(today) discuss **overall goals** and **desired analyses and products**

(today) review outstanding issues with satellite retrievals of C_a in the Bay

remaining issues ...

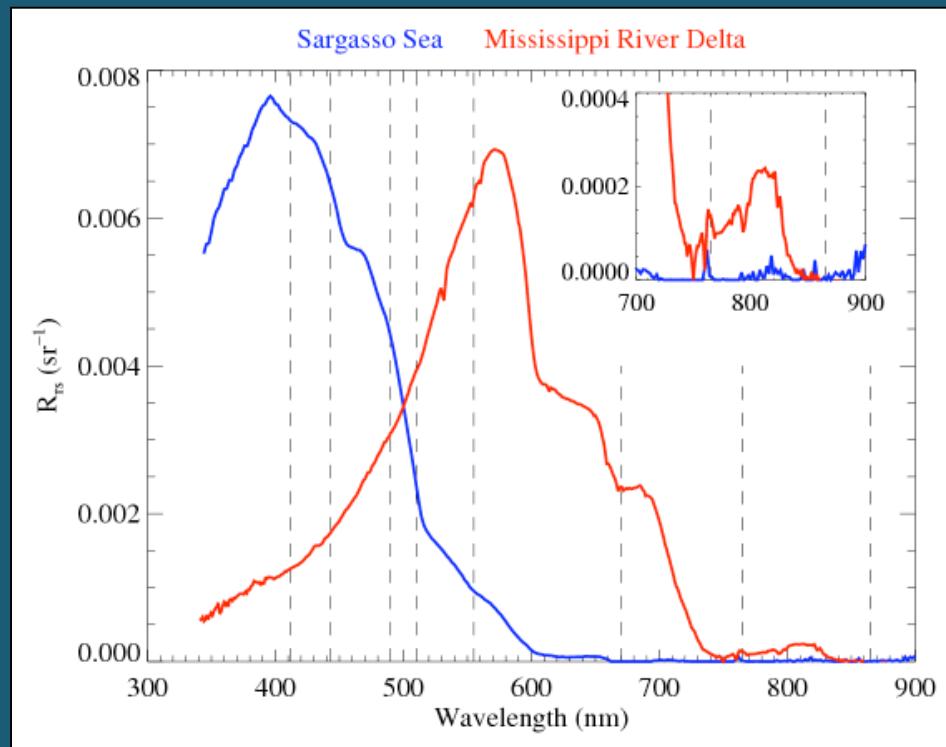


atmospheric correction:

- (1) non-uniform sub-surface light field
- (2) non-negligible L_w (NIR)
- (3) alternate atmospheric corrections
- (4) regional aerosol models (absorbing)
- (5) straylight contamination from land
- (6) anthropogenic emissions (e.g., NO_2)

spatial binning & mapping:

- (1) L2 (satellite view) versus L3 (averaged, gridded)
- (2) spatial resolution
- (3) application of C_a algorithm(s)
- (4) use of extended MODIS band suite



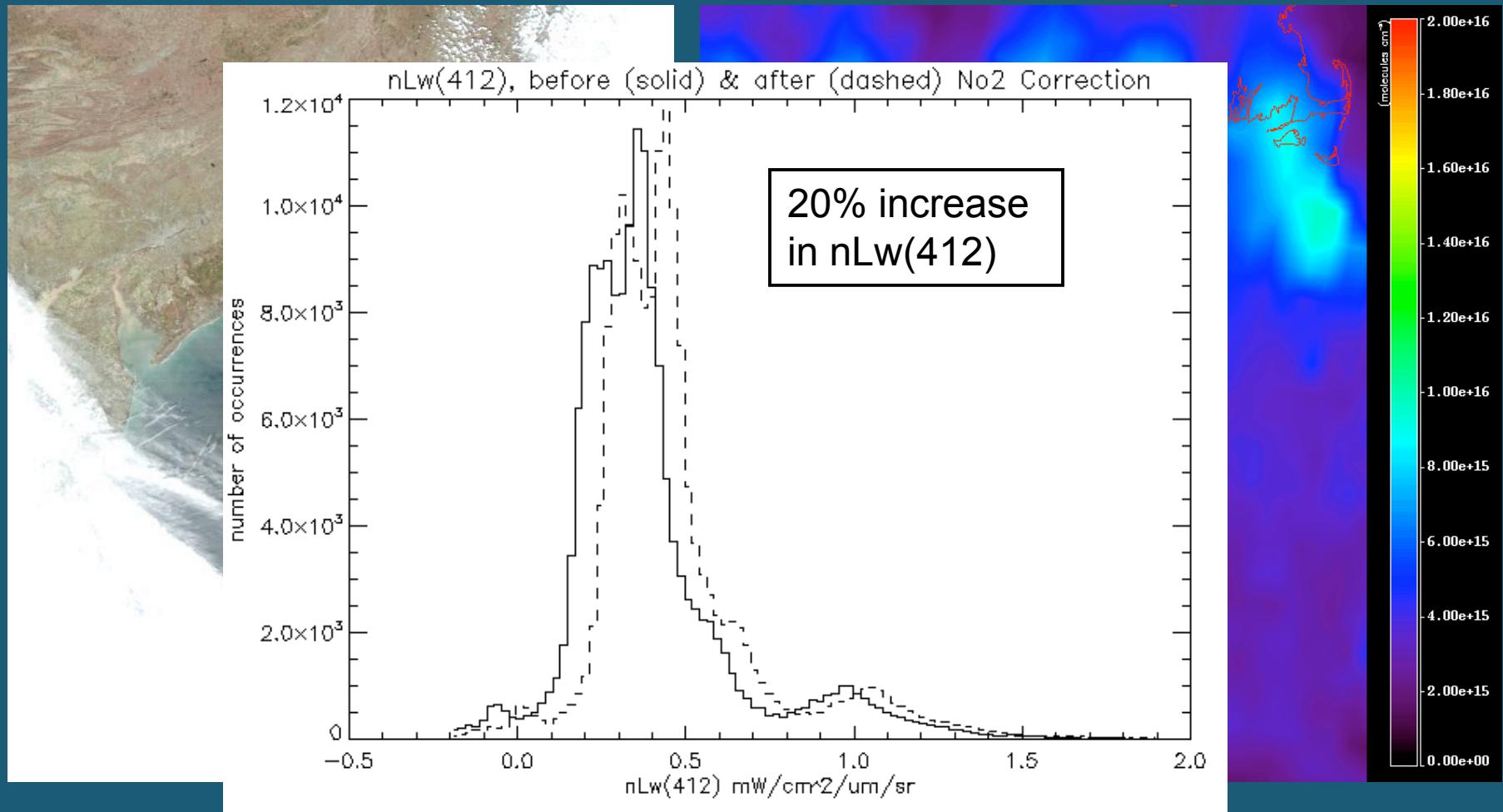
Challenges to Remote Sensing of Coastal and Inland Waters

- temporal and spatial variability
 - limitations of satellite sensor resolution and repeat frequency (multi-mission)
 - validity of ancillary data (reference SST, wind)
- straylight contamination from land
- non-maritime aerosols (dust, pollution)
 - region-specific models required
 - absorbing aerosols
- suspended sediments and CDOM
 - complicates estimation of $L_w(\text{NIR})$, model not $f_n(C_a)$
 - complicates correction for non-uniform subsurface light field (f/Q)
 - saturation of observed radiances
- anthropogenic emissions (NO_2 absorption)

Correction for NO₂ Absorption

MODIS/Aqua RGB

OMI/Aura Tropospheric NO₂

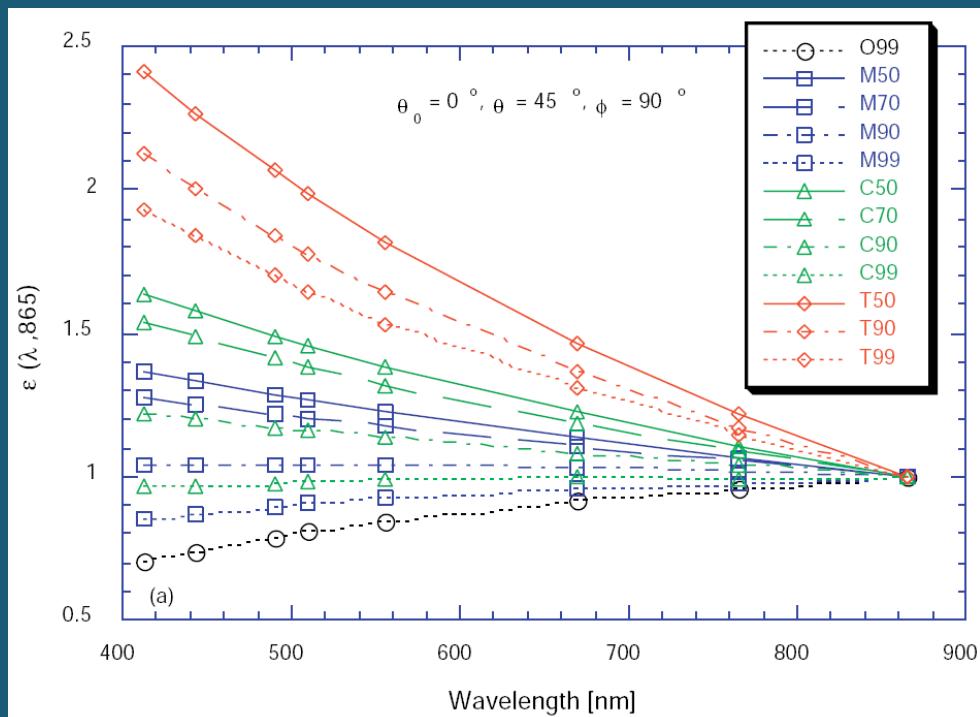


Can effect interpretation of CDOM contributions in bio-optical models like GSM01

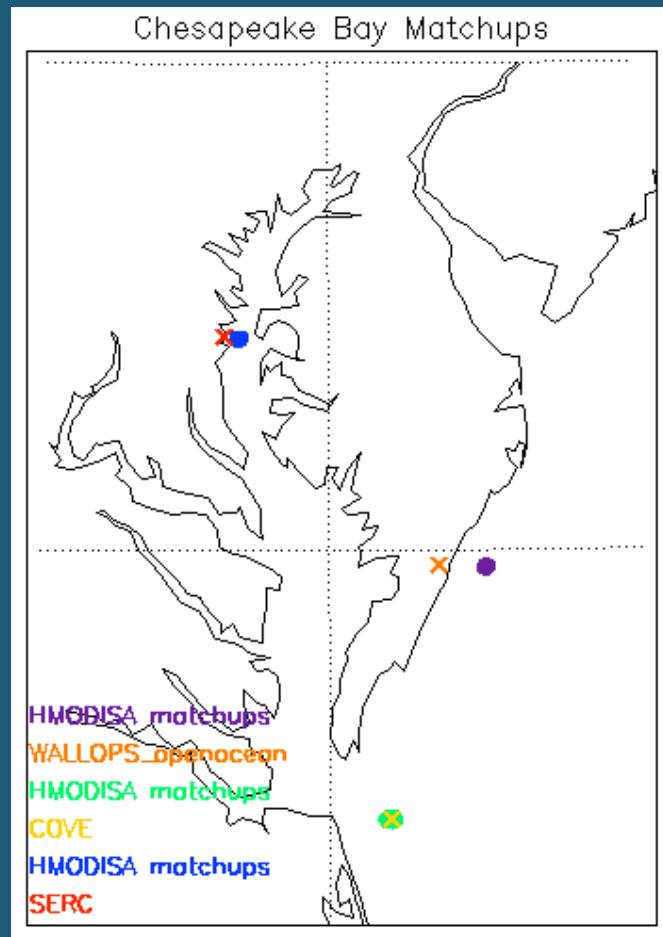
Development of regional aerosol models

Ahmad and Kwiatkowska

standard models for open ocean



AERONET sites
in situ aerosol properties



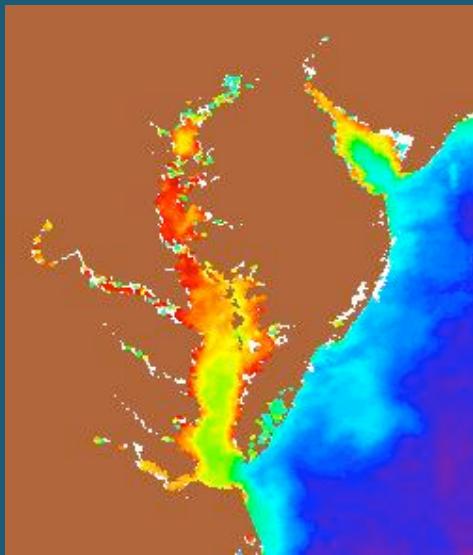
MODIS Land/Cloud Bands of Interest

| Band | Wavelength | Resolution | Potential Use |
|------|------------|------------|---------------------------------|
| 1 | 645 nm | 250 m | sediments, turbidity, IOPs |
| 2 | 859 | 250 | aerosols |
| 3 | 469 | 500 | C_a , IOPs, CaCO ₃ |
| 4 | 555 | 500 | C_a , IOPs, CaCO ₃ |
| 5 | 1240 | 500 | aerosols |
| 6 | 1640 | 500 | aerosols |
| 7 | 2130 | 500 | aerosols |

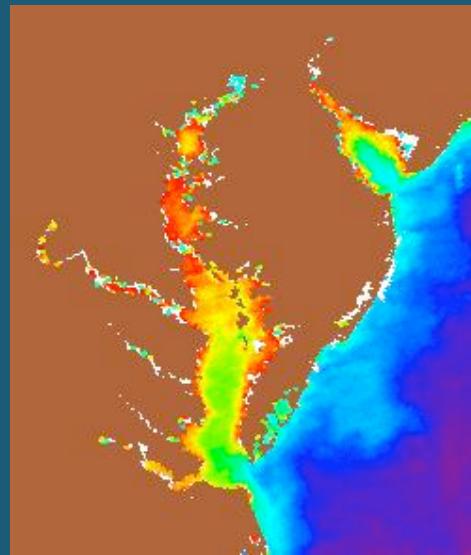
spatial resolution and expanded dynamic range come at the cost of increased digitization error (reduced sensitivity at ocean radiances) and reduced signal to noise

Chlorophyll: 1000-meter resolution

OC3 = f(443,488,551)



OC2 = f(469,555)



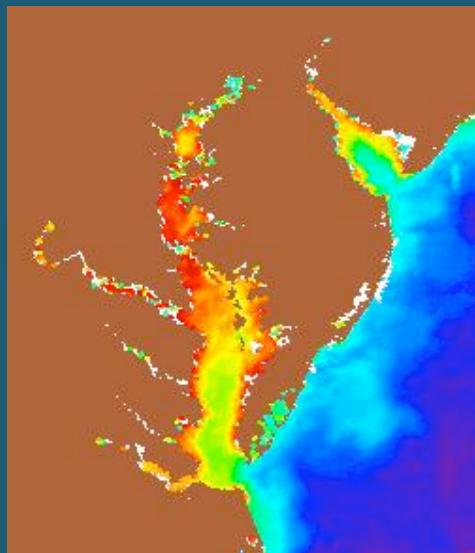
0.4

mg m^{-3}

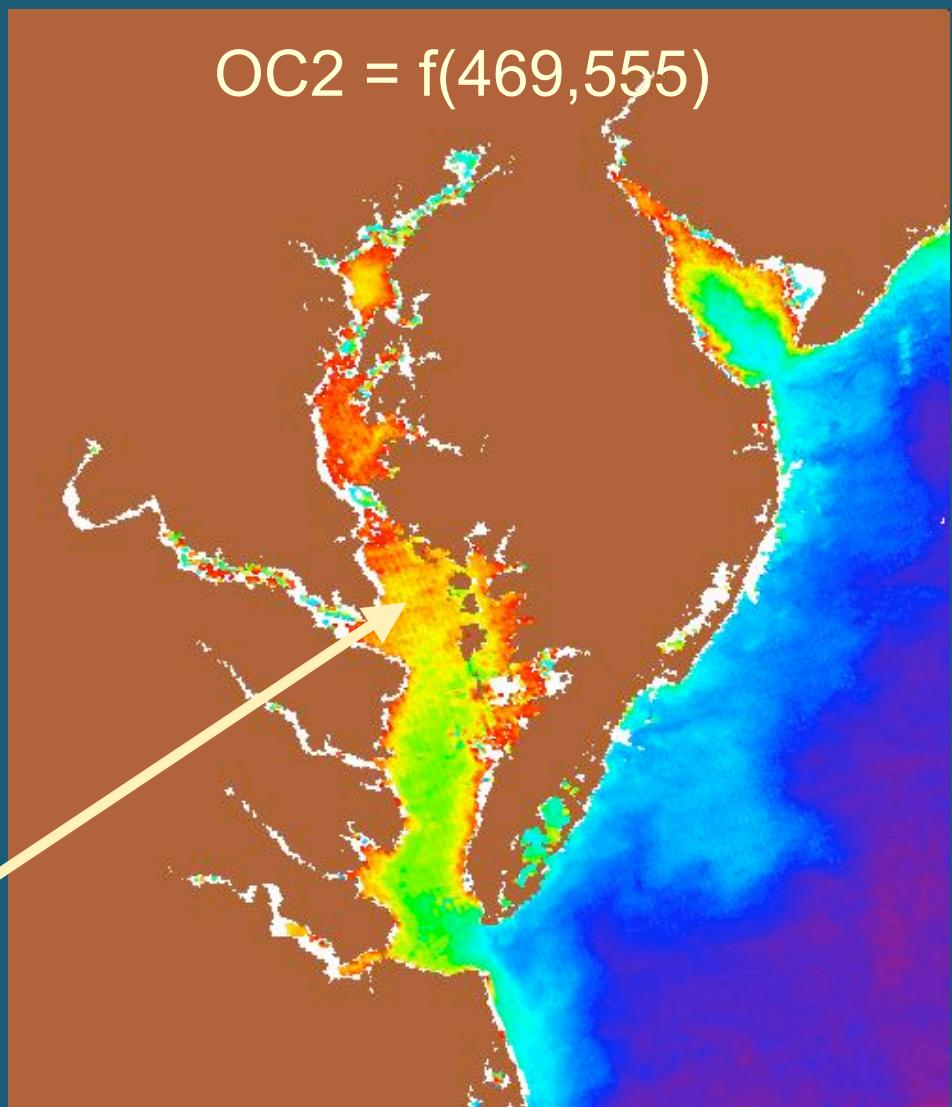
100

Chlorophyll: 1000 & 500-meter

OC3 = $f(443,488,551)$



OC2 = $f(469,555)$



Noise

0.4

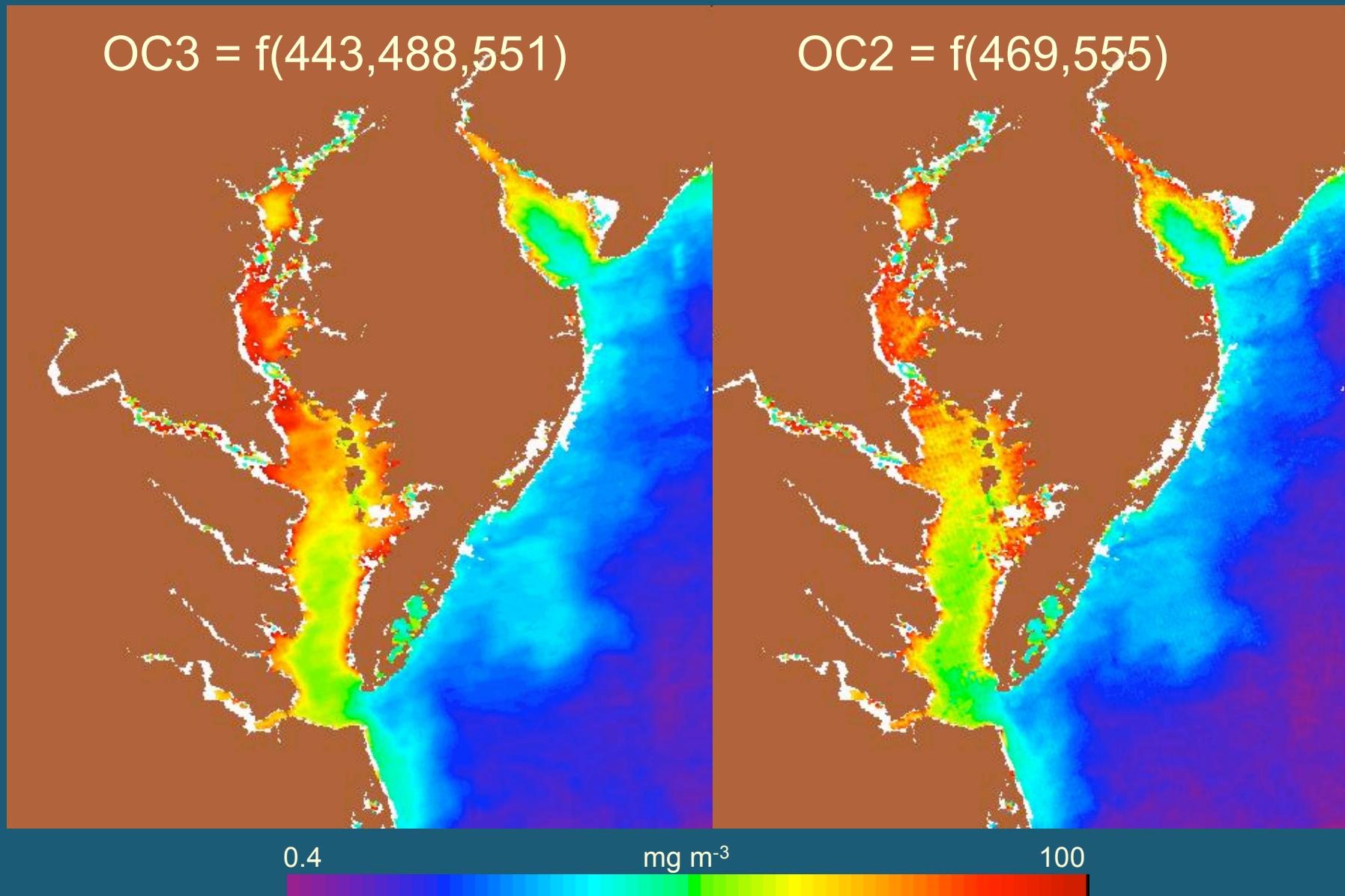
mg m⁻³

100

Chlorophyll: 500-meter Resolution

OC3 = $f(443,488,551)$

OC2 = $f(469,555)$



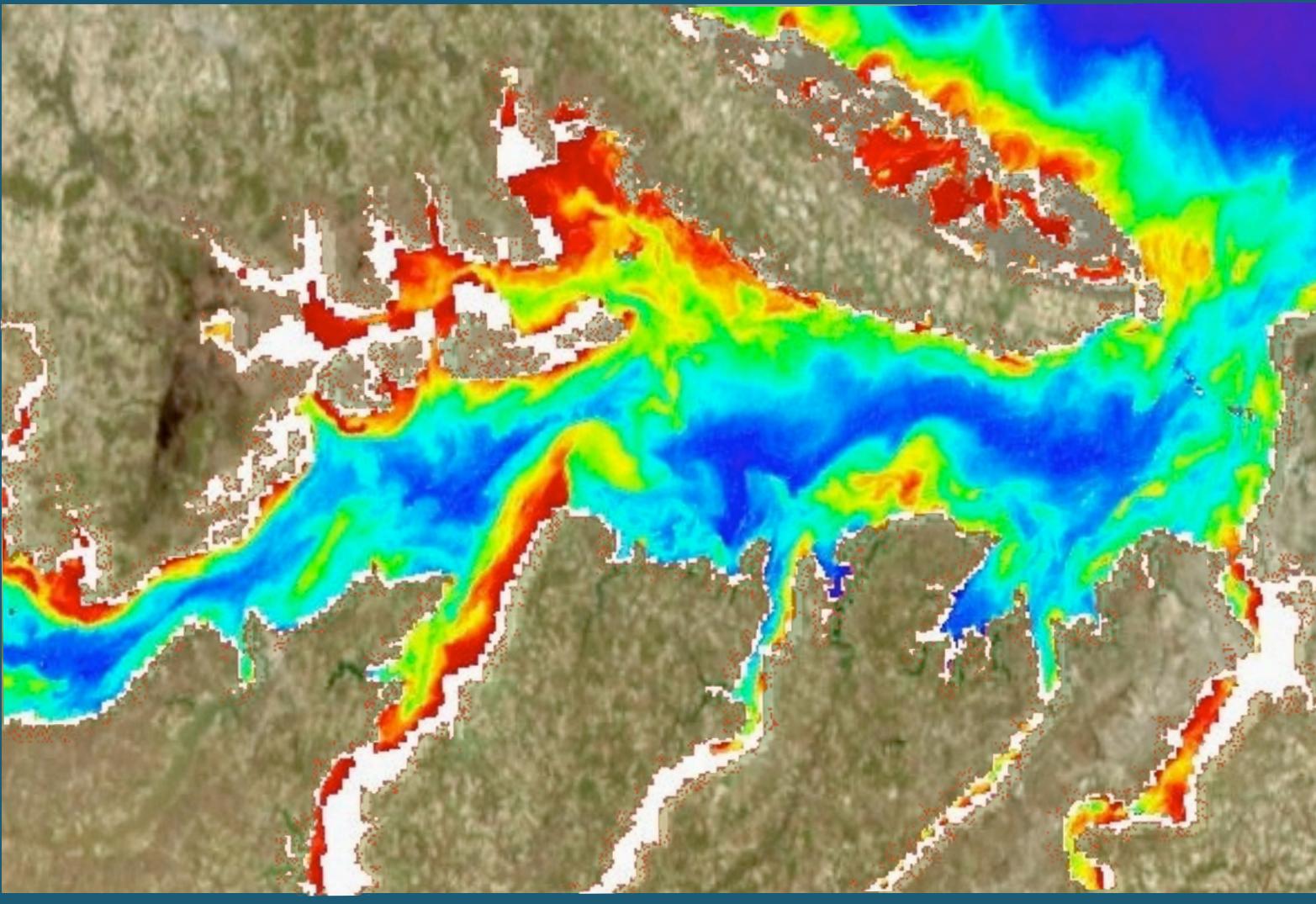
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| 4 | 555 | 500 | C_a , IOPs, CaCO ₃ |
| 5 | 1240 | 500 | aerosols |
| 6 | 1640 | 500 | aerosols |
| 7 | 2130 | 500 | aerosols |

RGB Image: 250-meter Resolution



nLw(645): 250-meter resolution



-0.1

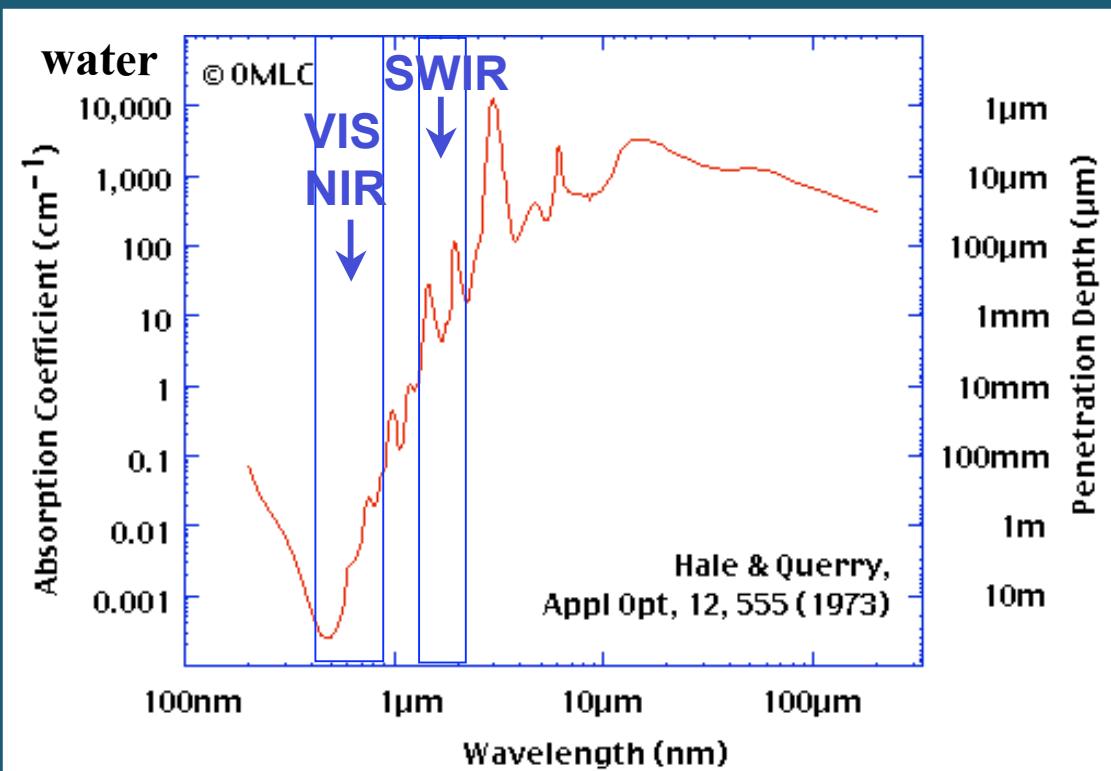
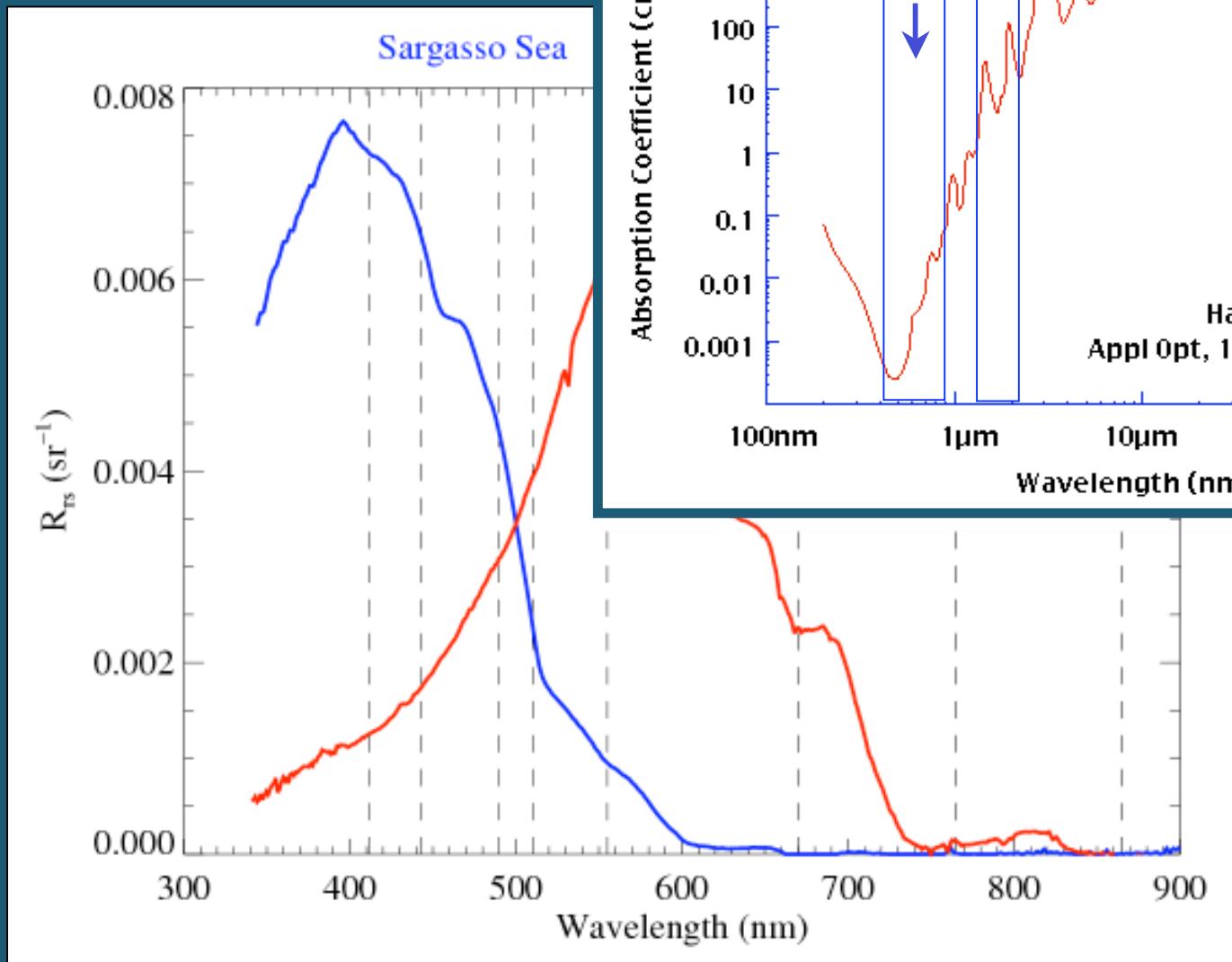
$\text{mW cm}^{-2} \mu\text{m}^{-1} \text{sr}^{-1}$

3.0

MODIS Land/Cloud Bands of Interest

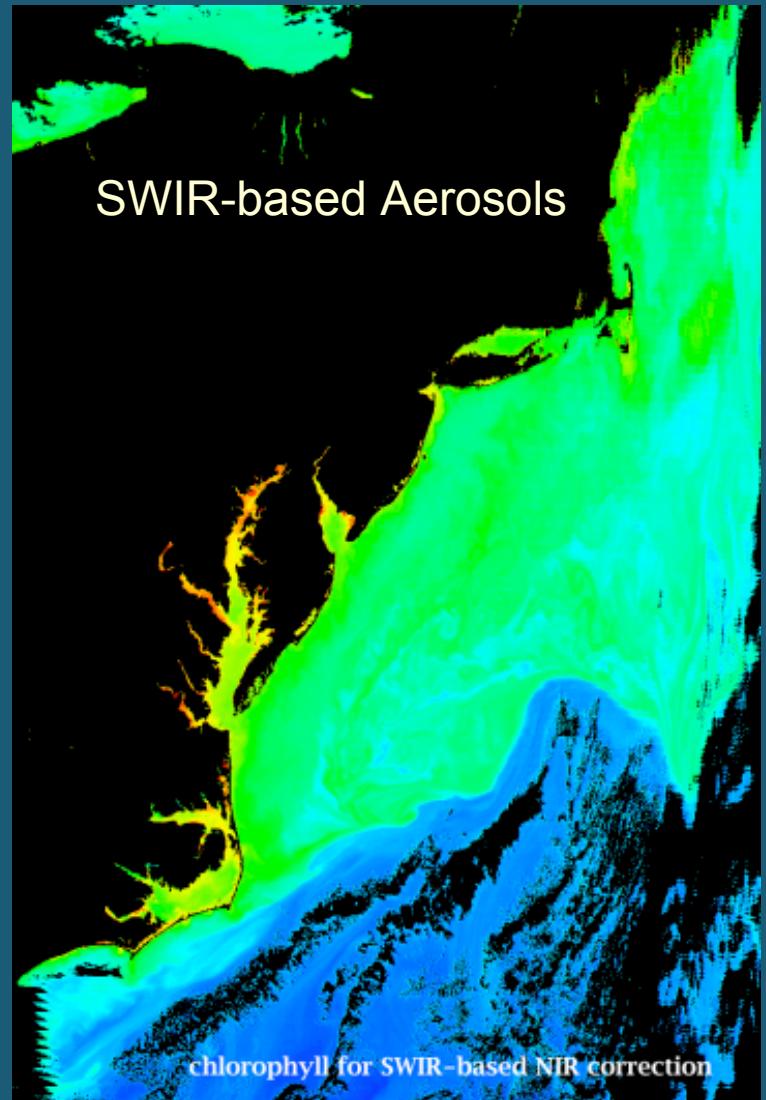
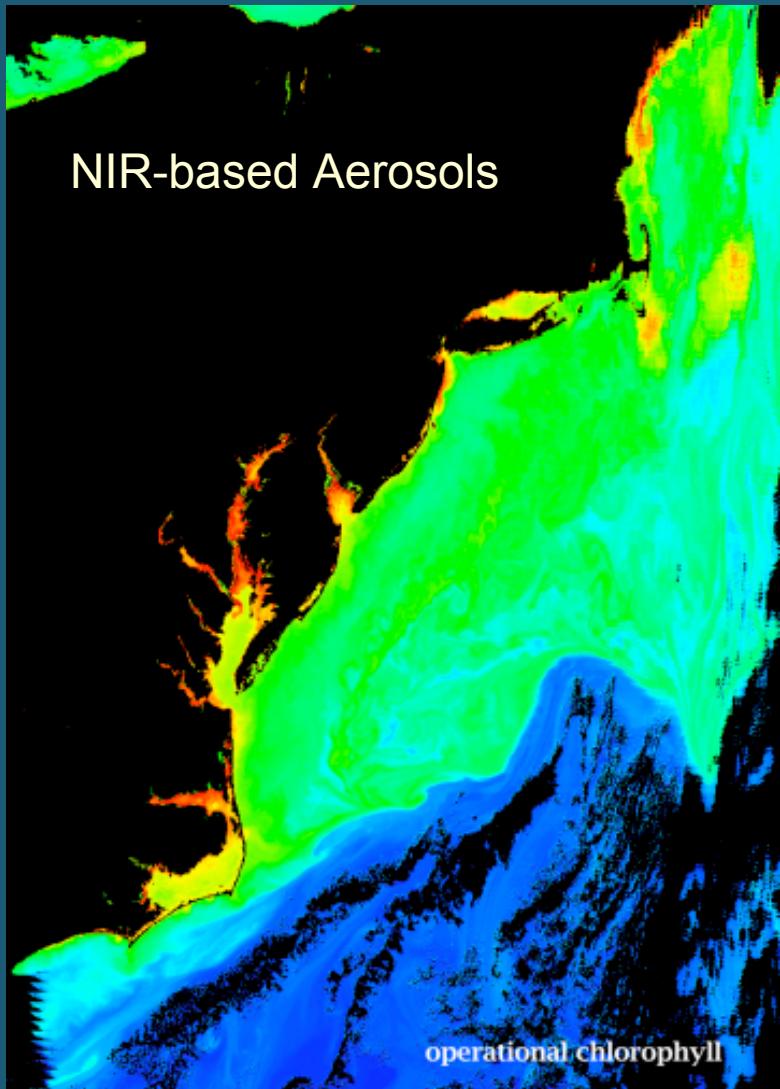
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SWIR

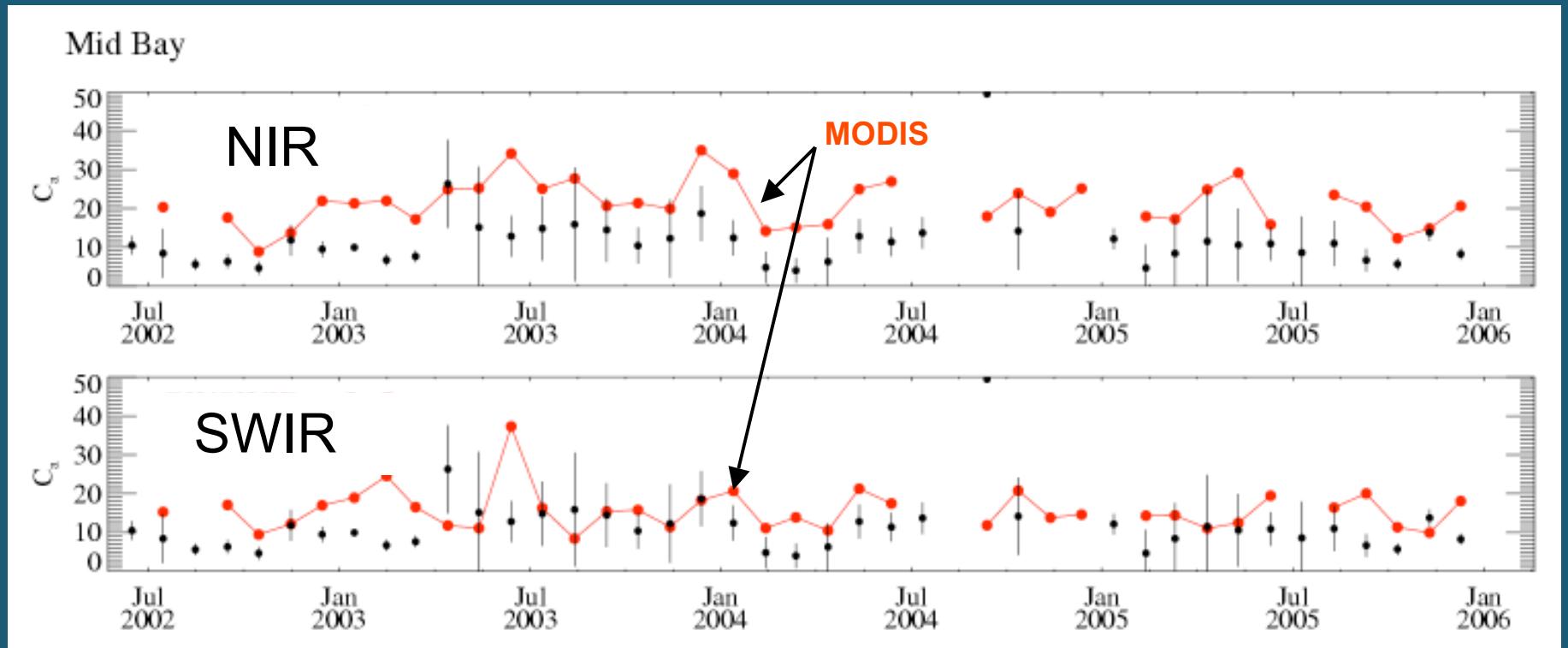


SWIR

Change in Chlorophyll Retrieval with Alternate Aerosol Determination Methods



Monthly Mean C_a Time-Series Comparison Mid Bay

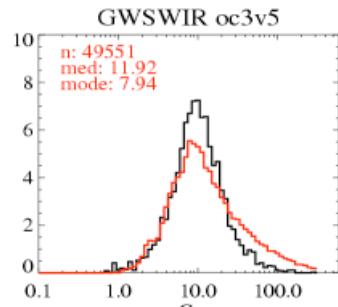
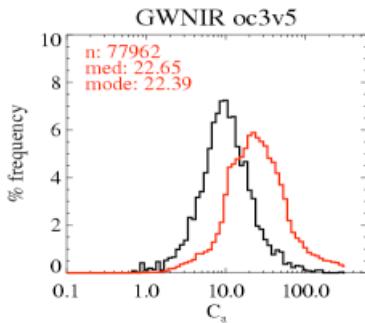


NIR

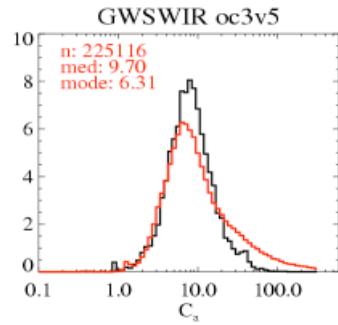
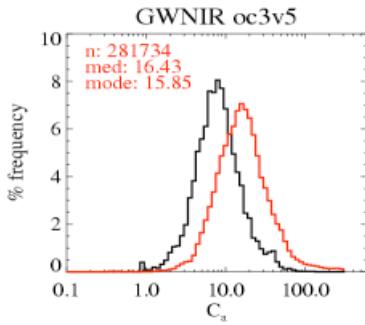
SWIR

Satellite vs In Situ

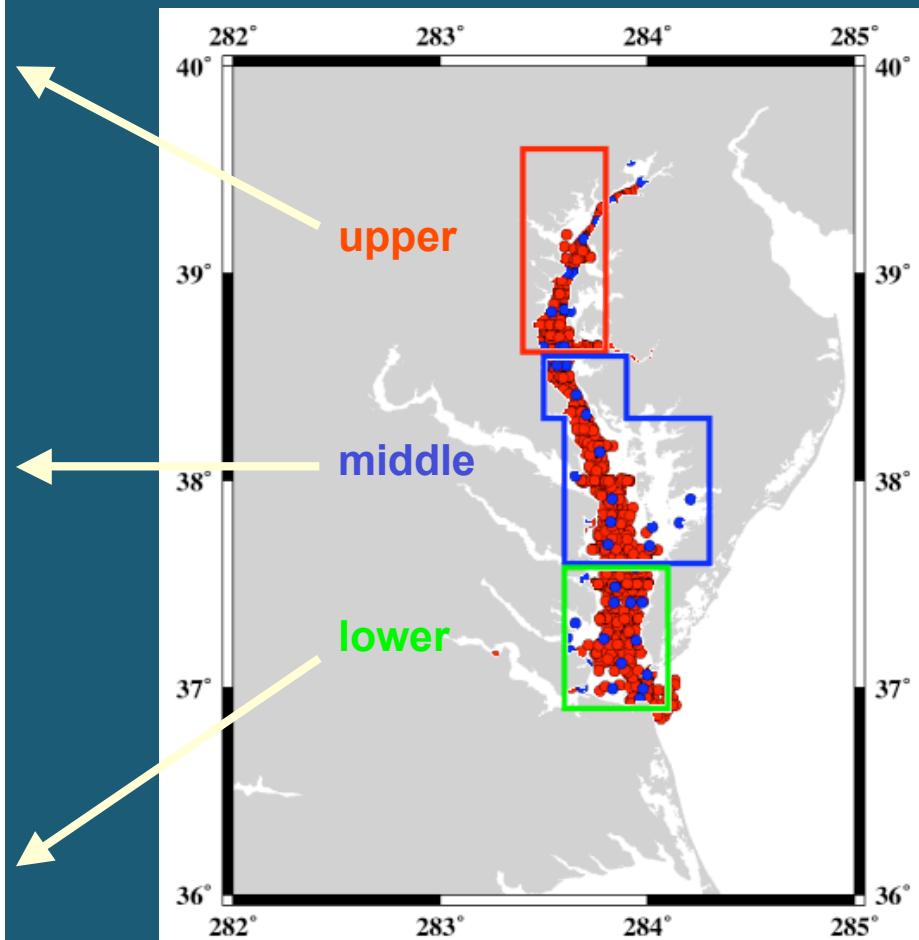
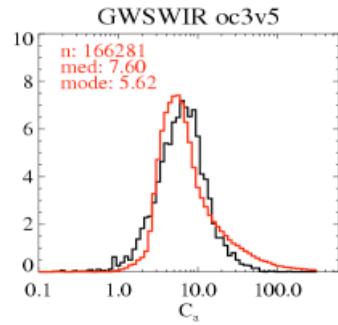
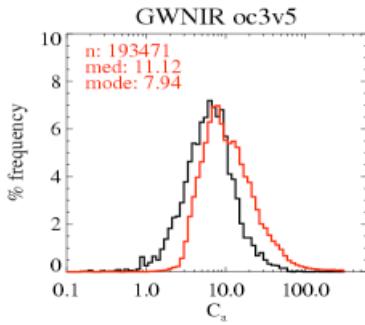
Upper Bay, ALL in situ = n: 3663, med: 10.52, mode: 10.00
color legend: in situ MODIS-Aqua



Mid Bay, ALL in situ = n: 5814, med: 8.43, mode: 7.94
color legend: in situ MODIS-Aqua



Lower Bay, ALL in situ = n: 7204, med: 6.50, mode: 6.31
color legend: in situ MODIS-Aqua



MODIS Granule Compositing

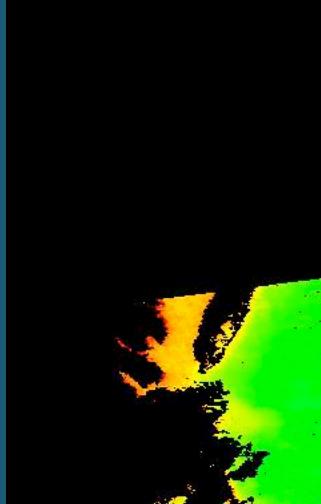
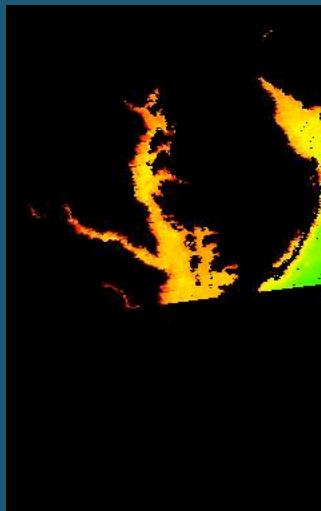
↑
time

extracted
granules

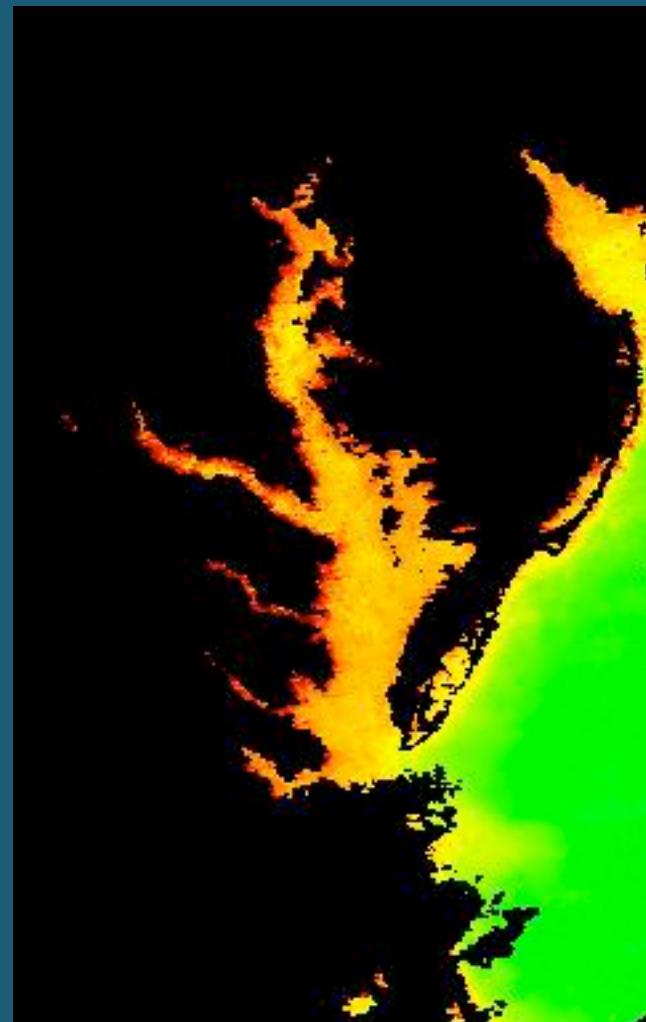


36N to 40N,
75W to 77.5W

mapped C_a



500-m L2 binned to 1km L3



Future Plans



Thank You !



Expanded MODIS Ocean Band Suite

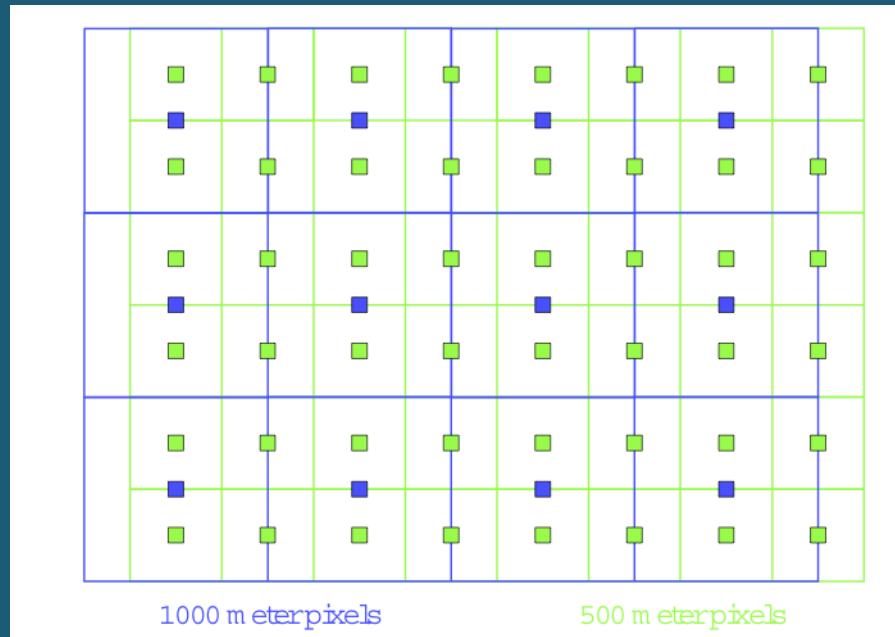
| Band Number | Wavelength (nm) | Band Width (nm) | Spatial Resolution (m) | SNR at L _{typ} | L _{typ} mW cm ⁻² μm ⁻¹ sr ⁻¹ | L _{max} mW cm ⁻² μm ⁻¹ sr ⁻¹ |
|-------------|-----------------|-----------------|------------------------|-------------------------|--|--|
| 8 | 412 | 15 | 1000 | 1773 | 7.84 | 26.9 |
| 9 | 443 | 10 | 1000 | 2253 | 6.99 | 19.0 |
| 3 | 469 | 20 | 500 | 556 | 6.52 | 59.1 |
| 10 | 488 | 10 | 1000 | 2270 | 5.38 | 14.0 |
| 11 | 531 | 10 | 1000 | 2183 | 3.87 | 11.1 |
| 12 | 551 | 10 | 1000 | 2200 | 3.50 | 8.8 |
| 4 | 555 | 20 | 500 | 349 | 3.28 | 53.2 |
| 1 | 645 | 50 | 250 | 140 | 1.65 | 51.2 |
| 13 | 667 | 10 | 1000 | 1962 | 1.47 | 4.2 |
| 14 | 678 | 10 | 1000 | 2175 | 1.38 | 4.2 |
| 15 | 748 | 10 | 1000 | 1371 | 0.889 | 3.5 |
| 2 | 859 | 35 | 250 | 103 | 0.481 | 24.0 |
| 16 | 869 | 15 | 1000 | 1112 | 0.460 | 2.5 |
| 5 | 1240 | 20 | 500 | 25 | 0.089 | 12.3 |
| 6 | 1640 | 35 | 500 | 19 | 0.028 | 4.9 |
| 7 | 2130 | 50 | 500 | 12 | 0.008 | 1.7 |

Multi-Resolution Implementation

Aggregation

| QKM | HKM | 1KM |
|----------------------|---------------------|---------------------|
| 645 nm | 469 nm | 412 nm |
| 859 nm | 555 nm | 443 nm |
| | 645 nm ¹ | 469 nm ³ |
| | 859 nm ¹ | 488 nm |
| 1240 nm | 531 nm | |
| 1640 nm | 551 nm | |
| 2130 nm | 555 nm ³ | |
| | 645 nm ² | |
| 667 nm | | |
| 678 nm | | |
| 748 nm | | |
| 859 nm ² | | |
| 869 nm | | |
| 1240 nm ³ | | |
| 1640 nm ³ | | |
| 2130 nm ³ | | |
| 3.9 um | | |
| 4.0 um | | |
| 11 um | | |
| 12 um | | |

Interpolation



from Gumley, et al.

Observed (TOA) radiances, geolocation, radiant path geometries interpolated or aggregated to a common resolution at start.

MODIS Ocean Band Suite

| Band Number | Wavelength (nm) | Band Width (nm) | Spatial Resolution (m) | SNR at L _{typ} | L _{typ} mW cm ⁻² μm ⁻¹ sr ⁻¹ | L _{max} mW cm ⁻² μm ⁻¹ sr ⁻¹ |
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Expanded MODIS Ocean Band Suite

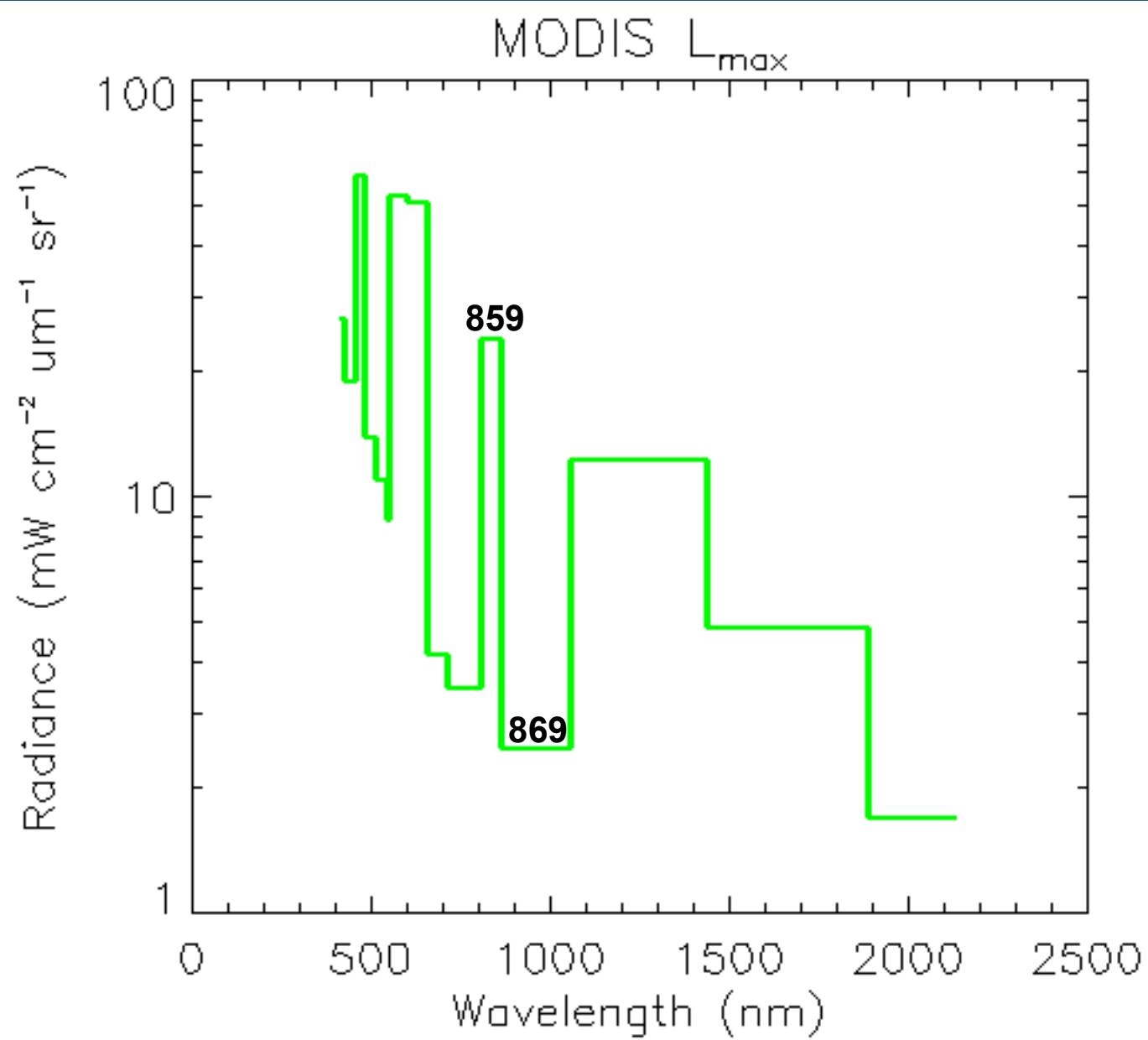
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| 1 | 645 | 50 | 250 |
| 13 | 667 | 10 | 1000 |
| 14 | 678 | 10 | 1000 |
| 15 | 748 | 10 | 1000 |
| 2 | 859 | 35 | 250 |
| 16 | 869 | 15 | 1000 |
| 5 | 1240 | 20 | 500 |
| 6 | 1640 | 35 | 500 |
| 7 | 2130 | 50 | 500 |

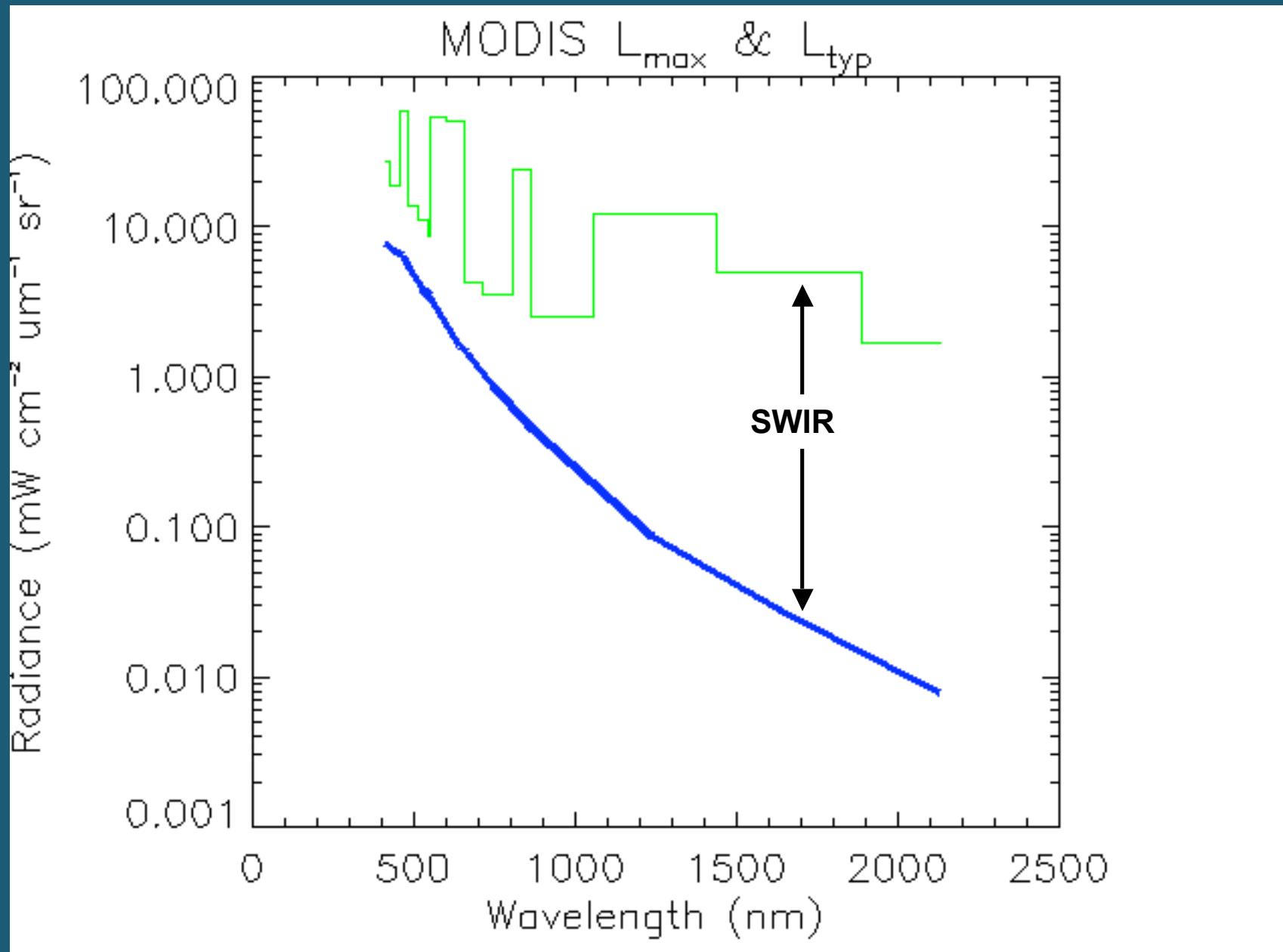
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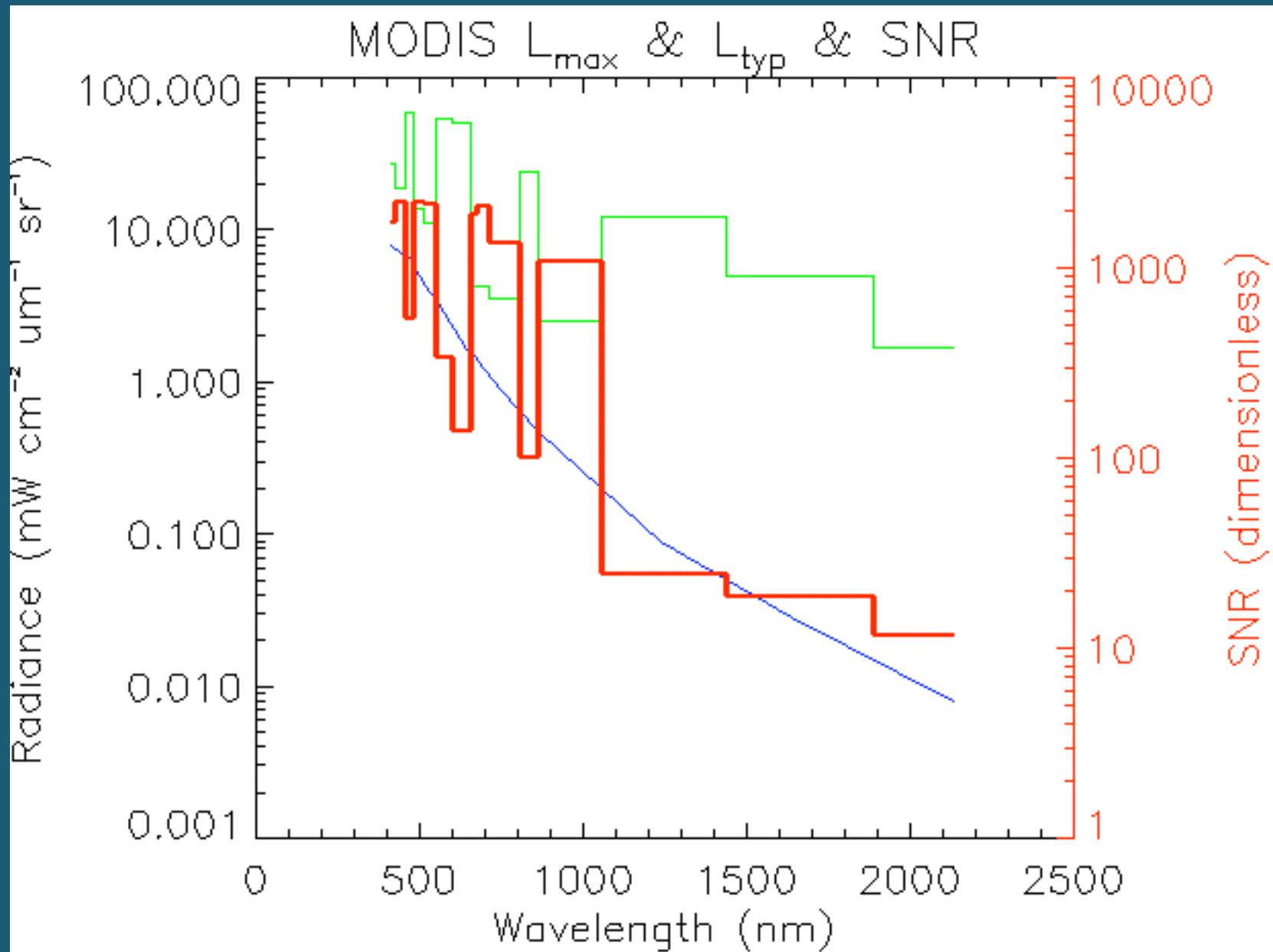
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| 14 | 678 | 10 | 1000 | 4.2 |
| 15 | 748 | 10 | 1000 | 3.5 |
| 2 | 859 | 35 | 250 | 24.0 |
| 16 | 869 | 15 | 1000 | 2.5 |
| 5 | 1240 | 20 | 500 | 12.3 |
| 6 | 1640 | 35 | 500 | 4.9 |
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Expanded MODIS Ocean Band Suite

| Band Number | Wavelength (nm) | Band Width (nm) | Spatial Resolution (m) | SNR at L _{typ} | L _{typ} mW cm ⁻² μm ⁻¹ sr ⁻¹ | L _{max} mW cm ⁻² μm ⁻¹ sr ⁻¹ |
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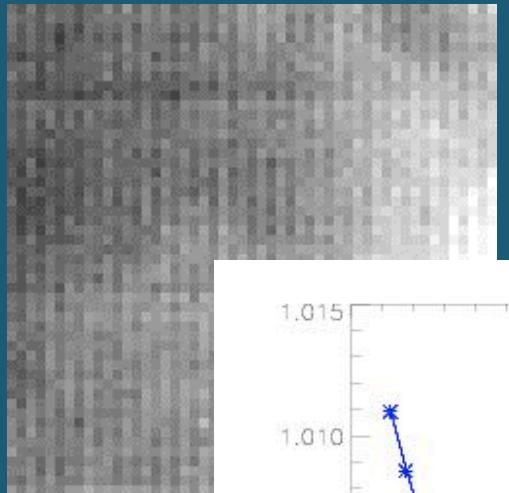




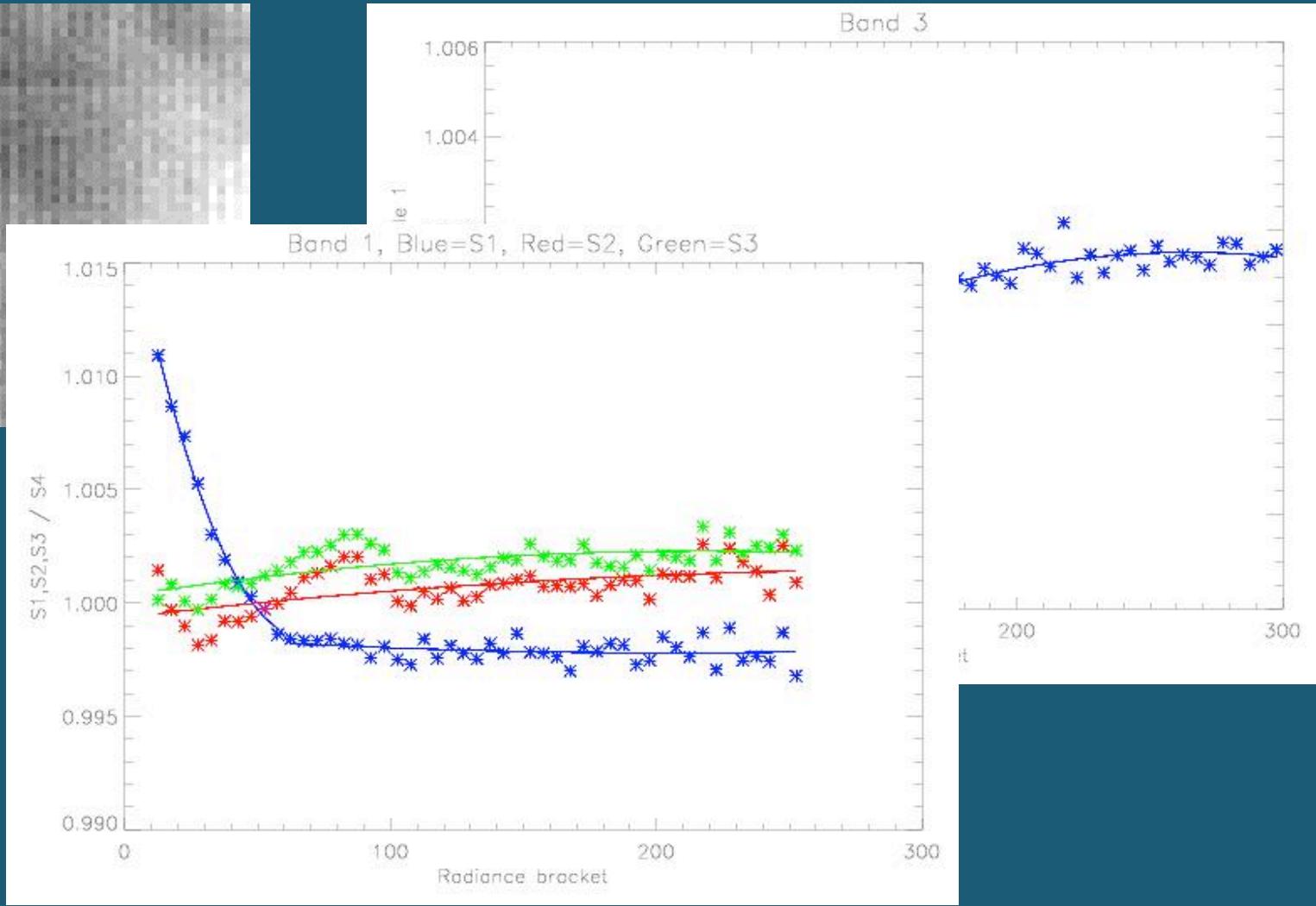


Detector and Sub-sample Striping

TOA Radiance 469 nm



Ratio of Adjacent Samples Along Scan, 469 nm



Effects of the Atmosphere

- Gaseous absorption (ozone, water vapor, oxygen)
- Rayleigh scattering by air molecules
- Mie scattering and absorption by aerosols (haze, dust, pollution)
- Polarization (MODIS response varies with polarization of signal)

Rayleigh (80-85% of total signal)

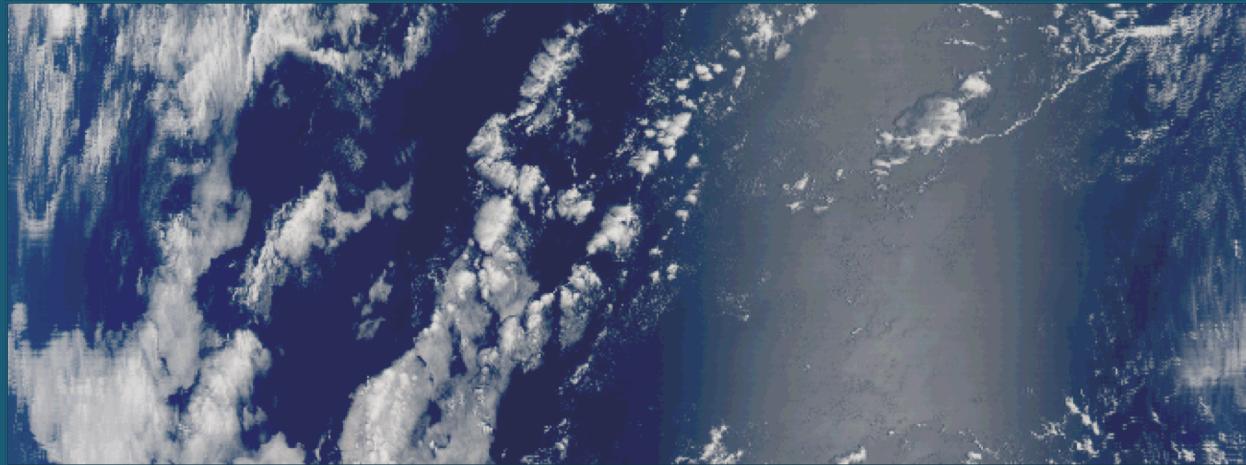
- small molecules compared to nm wavelength, scattering efficiency decreases with wavelength as λ^{-4}
- reason for blue skies and red sunsets
- can be accurately approximated for a given atmospheric pressure and geometry (using a radiative transfer code)

Aerosols (0-10% of total signal)

- particles comparable in size to the wavelength of light, scattering is a complex function of particle size
- whitens or yellows the sky
- significantly varies and cannot be easily approximated

Surface Effects

Sun Glint



White Caps



Corrections based
on statistical models
(wind & geometry)

Aerosol Determination in Visible Wavelengths

Given retrieved aerosol reflectance at two λ ,
and a set of aerosol models $fn(\theta, \theta_0, \phi)$.

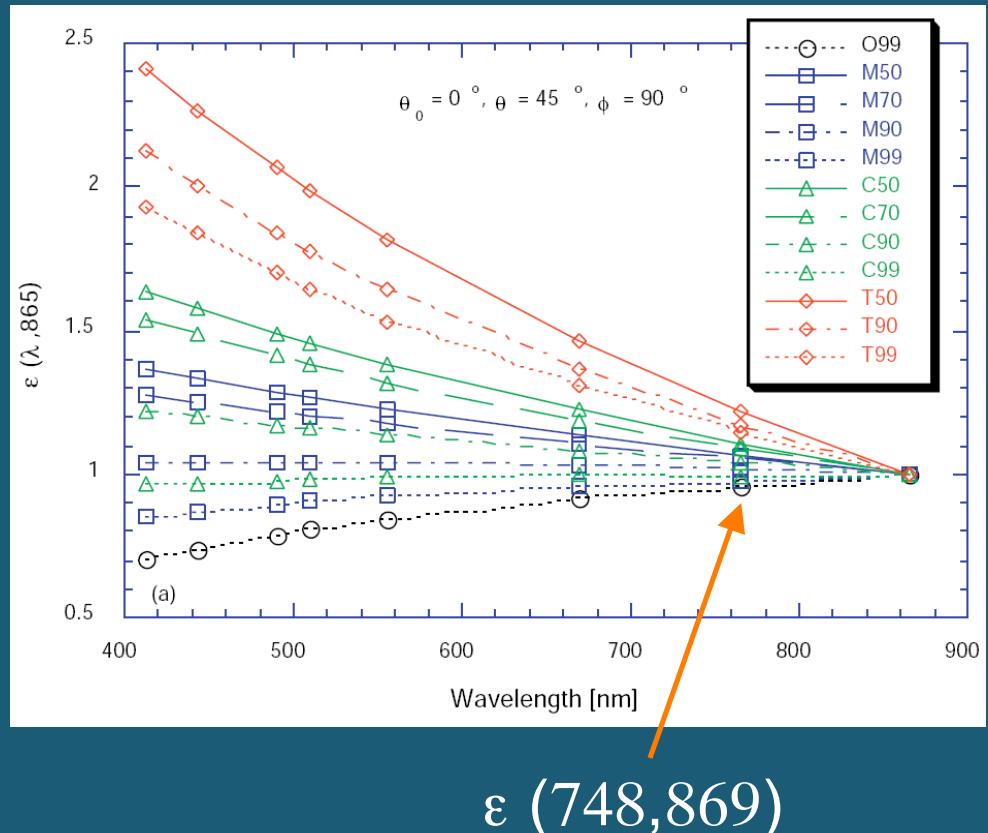
$$\rho = \frac{\pi L}{F_0 \cdot \mu_0}$$

$\rho_a(748) \& \rho_a(869)$

$\rho_a(\text{NIR})^{\text{model}} \Rightarrow \rho_{\text{as}}(\text{NIR})$

$$\varepsilon(748, 869) = \frac{\rho_{\text{as}}(748)}{\rho_{\text{as}}(869)}$$

$$\varepsilon(\lambda, 869) = \frac{\rho_{\text{as}}(\lambda)}{\rho_{\text{as}}(869)}$$



Challenges to Remote Sensing of Coastal and Inland Waters

- Temporal and spatial variability
 - Limitations of satellite sensor resolution and repeat frequency
 - Validity of ancillary data (reference SST, wind)
- Straylight contamination from land
- Non-maritime aerosols (dust, pollution)
 - Region-specific models required
 - Absorbing aerosols
- Anthropogenic emmissions (NO_2 absorption)
- Suspended sediments and CDOM
 - Invalid estimation of $L_w(\text{NIR})$, model not $f_n(C_a)$
 - Saturation of observed radiances

Median Percent Difference from *In Situ* Chlorophyll

| Region | Method | All | Spring | Summer | Fall | Winter |
|--------|--------|-------|--------|--------|-------|--------|
| Upper | NIR | 115.3 | 141.5 | 104.7 | 185.8 | 151.2 |
| | SWIR | 13.3 | 25.2 | 20.5 | 48.6 | 35.8 |
| Middle | NIR | 94.9 | 87.7 | 122.2 | 113.9 | 148.4 |
| | SWIR | 15.1 | -5.6 | 19.9 | 31.3 | 62.2 |
| Lower | NIR | 71.1 | 110.8 | 71.4 | 43.2 | 123.0 |
| | SWIR | 16.9 | 4.0 | -4.6 | 13.5 | 72.0 |

SWIR-based aerosol determination significantly reduces bias in C_a retrievals relative to historical record for all seasons.

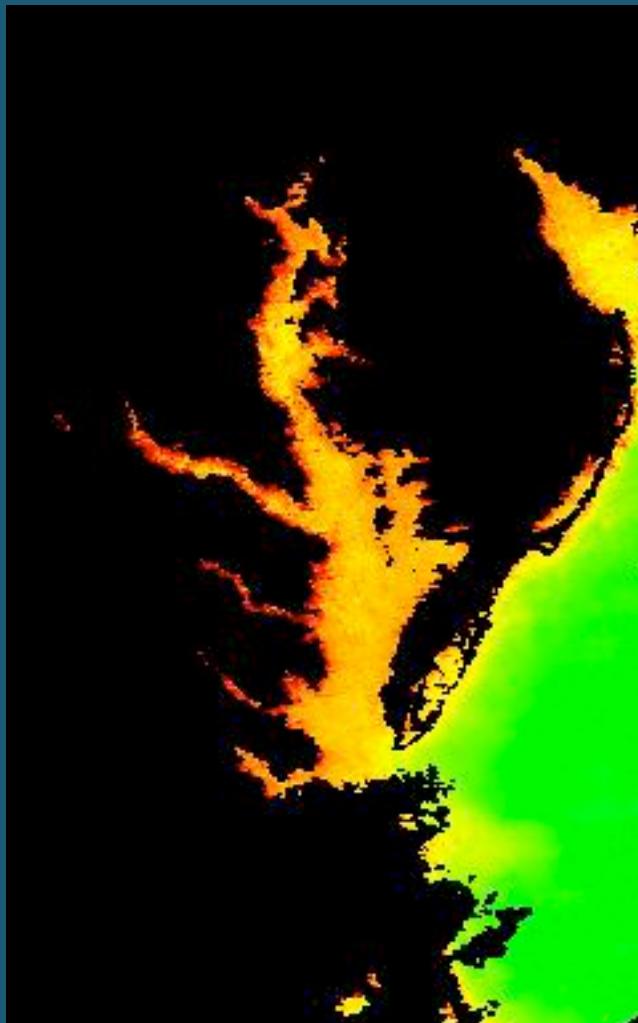
Best improvement in Spring-Summer, where aerosol optical thickness (SWIR signal) is highest.

Evaluation of Aerosol Determination Methods in Chesapeake Bay

- 1 Aerosol determined via NIR at 748 and 869 nm
 - 2 Aerosol determined via SWIR at 1240 and 2130 nm
-
- Processed 150 MODIS/Aqua scenes over Chesapeake Bay to retrieve OC3 Chlorophyll at 1km resolution.
 - Compared with historical record of *in situ* C_a

MODIS Granule Compositing

500-m L2 binned to 1km L3



1km L2 binned to 1km L3

